Baluns for UHF Transmit Arrays

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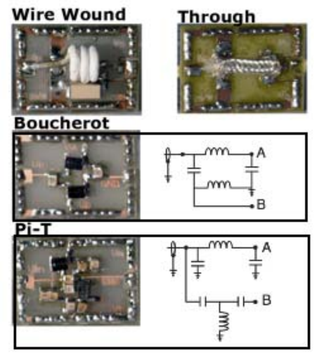
Introduction: Common-mode currents contribute to radiation loss, and thereby reduce the power delivered to the load by transmit coils. As radiation losses rapidly increase with frequency, the losses are more dramatic at 7T. In transmit arrays, the potential losses due to common-mode currents increase with the number of feed ports. These common mode currents are reduced by baluns, which convert the unbalanced signal from a coaxial line to the balanced load of a loop-type coil element. Based on earlier conclusions [1], we investigated the performance of wide-band and narrow-band 180° baluns at 7T, using an adapted mixed-mode scattering parameter measurement. Peterson [1] claimed that the "π−τ" lumped lattice balun delivers a true balanced excitation, i.e. 180° phase between the voltages delivered to the coil terminals, while the Boucherot bridge balun fails to provide this, giving only a 90° phase. However, this claim was often challenged at ISMRM 2010, with demonstrations through circuit transformations that both baluns were equivalent. We have investigated several outstanding questions, in the context of a 4-channel head coil array for parallel transmit at 7T, this time including differential-mode insertion loss measurements with a network analyzer.



Methods: To evaluate different common-mode suppression techniques, we created motherboards for 3-port network analyzer measurements and also integrated the same motherboard into the feed ports of each element into a 4-element transmit array. We fabricated four of each of the following daughter boards: π−τ lattice balun, Boucherot bridge balun, wire-wound balun, and a short coaxial through line in place of a balun. The π−τ lattice balun, with π and τ quarter-wave sections, as well as the Boucherot balun, were built with reactances equal to 50 ohms. The common mode rejection (CMR, the ratio of the transmitted common mode signal to the differential mode signal) and insertion loss (IL) of the daughter boards were assessed with a network analyzer. The daughter boards were inserted into a board with three coaxial connectors with common ground. Port 1 was connected by a cable to the generator side of the balun, and the branches of the balun were connected one at a time to Port 2, with the other branch terminated by a load. The baluns have 50-ohm differential impedances, and therefore each branch presents only 25 ohms. Therefore we calibrated the plane of the test board to a virtual impedance of 25 ohms. The coil feed ports were connected one at a time to the network analyzer, with the other side was terminated by a 25-ohm load. CMR and insertion loss (IL) were calculated by converting S-parameter measurements to mixed-mode measurements to the phase and amplitude imbalances between the two branches of the feed port [2]. IL combines the losses of the two branches with the losses due to the phase mismatch between the branches. We adjusted component values of each of the lumped-element balun types for the same common-mode suppression (CMR <-20 dB) at 297.2 MHz. A wire-wound balun was created by winding 3 loops of coaxial cable and adding a resonant parallel capacitance (5.6 pF). The wire-wound balun was intentionally adjusted without the aid of our quantitative test method, using a single-channel sniffer coil, to adjust the resonant frequency of the loop to 1 MHz above the operating frequency. Note that the coaxial cable was only the small section intended for use in the balun. The through daughter board was fabricated from the same coaxial cable as the wire-wound balun. A four-element transceiver array was tuned and matched for each daughterboard condition. The array had a 300-mm outer diameter and a 400-mm shield made of polyimide silver mesh. The square elements were made of 1-mm wide copper foil, measured 150 mm by 270 mm, and contained 8 distributed capacitors (which includes the parallel tapped matching capacitor). The elements were inductively decoupled (~40 nH mutual inductance, <-16dB), and separated by a 13 mm (+/- 2 mm) gap. The coil was loaded by a cylindrical phantom containing 7.3 L of a solution with 1.24g nickel sulphate and 2.62 g salt per liter. Transmit efficiency was assessed as the recommended transmit voltage for the phase shim, based on flip-angle maps (presaturated Turbo Flash: TR/TE/TI: 2000/1.9/300 ms, central axial slice, 3 x 3 x 8 mm^3 voxels, 10° excitation, 45° rectangular 500 μs saturation pulse).

Results: All baluns provided <-20 dB CMR**,** and showed substantially reduced required power for a 90° flip pulse (see Table). Comparison of the power difference required for the through case gives an indication of the severity of common-mode-current power loss for this array at 7T. Ranking of the transmit efficiency of the baluns follows the level of insertion loss. The IL of the setup (through board) was -1 dB. The wire wound balun had the least insertion loss and provided the highest transmit efficiency. Fine tuning of the wire-wound balun using the 3-port measurement did not increase the transmit efficiency despite improving the CMR to -35 dB. Repeated measures (n=10) of transmit efficiency failed to show a significant difference between the wire-wound balun tuning methods. Conversely, the untuned lumped element baluns provided > -15 dB CMR and were worse than no balun. The π−τ balun was more narrowband than the Boucherot balun, and when untuned had a CMR > -11 dB.

Discussion: For reliable balance measurements the conditions for analyzing each branch of the balun must be identical. For this reason, each branch was analyzed one at a time [3]. This strategy echoed the work of Belken [2], and further included a measure for IL and a different characterization of common-mode suppression. In circuit simulation of the lumped element baluns, the CMR was unaffected when the balanced ports were modeled with 25 ohm characteristic impedance instead of 50 ohm. However, in practice we also saw a change in the phase and amplitude balance, and CMR. Transmit-power limitations restrict the available MR techniques at ultra high field (UHF) strengths, and baluns can improve transmit efficiency for UHF. Baluns help assist subject safety by placing a virtual ground along the centerline of a loop coil, and also by reducing the highly variable coupling of currents to the environment surrounding the coil. Mixed-mode propagation along coaxial lines is assumed to be negligible in coil design and safety simulations, and therefore must be properly handled by coil engineers. We found an average twofold improvement in transmit efficiency when implementing baluns for an array of transmit coils, as compared to the single-element study (with only gradient shield) presented at ISMRM 2011. The measurements presented assist in implementing lumped element lattice baluns, but we did not observe improved transmit efficiency for the array presented when using the complex baluns or the more involved tuning method for the wire-wound baluns.
Based on our findings, we have built wire-wound baluns (as a balun or cable trap). We found that the influence of long cable lengths can be overcome by wrapping the excess cable around a ferrite core during tuning.

				Wirewound	
	Thru	PiT	Boucherot	Pick-up Tuned	3-port Tuned
CMR	-11 dB	-25 dB	-25 dB	-27 dB	-36 dB
$IL-IL_{thru}$	—	-3.5 dB	-2.4 dB	-0.5 ± 0.1 dB	-0.2 ± 0.1 dB
90° Power	2.3 kW	1.8 kW	1.7 kW	1.6 kW	
$1-(Power/Power_{thru})$	—	21%	24%	30%	

References: [1] Peterson et al, ISMRM 2002; [2] Belken, IEEE Microwave Magazine, December 2006: 86-99; [3] Bockelman et al, IEEE Trans. Microwave Theory and Techniques, 1995 (43): 1530-1539

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